"TouchBall": A Design and Evaluation of a Hand-held Trackball based Touch-Haptic Interface

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ABSTRACT
In this paper, we present a design and an evaluation of a hand-held trackball based touch-haptic interface, named "TouchBall." Using a trackball mechanism, the device provides flexibility in terms of directional degrees of freedom. It also has an advantage of a direct transfer of force feedback through frictional touch (with high sensitivity), thus requiring only relatively small amount of inertia. This leads to a compact hand-held design appropriate for mobile and 3D interactive applications. The device is evaluated for the detection thresholds for directions of the force feedback and the perceived amount of directional force. The refined directionality information should combine with other modalities with less sensory conflict, enriching the user experience for a given application.

Author Keywords
Interface, haptic, touch, mobile, hand-held, directional navigation.

ACM Classification Keywords
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION AND RELATED WORK

With the explosion and versatility of the mobile and hand-held computing or interaction devices, much effort has been put into the provision of haptic feedback in addition to the usual visual and aural. The most conventional approach has been the use of small vibrating motors, which are mostly just sufficient to indicate the occurrence of physical interaction events, namely collision. While researchers have looked at ways to simulate other types of information by controlling the vibrating signal (e.g. for texture simulation) [12] and by combining with other modalities [1], vibrating motors are still inherently limited in terms of conveying any directional or "simulated" inertial information.

Other researchers have looked at using small sized gyros [13], slider-crank mechanisms [4], moving weights [3] and rotating wheels [2] to create inertial sensation with limited directionality (usually only one dimension). However, these devices suffer from a lowered perception due to the indirect nature of the sensing through the attached housing/handles of the devices. MacLean et al. proposed a hand-held haptic controller in which a user actually touches rotating wheel for a more direct transfer of the stimulation [9]. The simplicity allowed for a highly ergonomic and light weight controller design. However, the applications were limited by the directionality (one) such as simple selection and browsing control. Engel et al. used a trackball device similar to ours, however focused on the issue of providing a combined contextual feedback for currently presented and expected information [14]. Their work has inspired us for a similar approach. We use a portable trackball to provide more directionality for 2D/3D applications such as navigation and physical engagement (e.g. hitting a ball coming in an angle). In this paper, we present the design and psychophysical evaluation for "TouchBall," a hand-held trackball based touch-haptic interface (See Figure 1). More specifically, the device is evaluated for the detection thresholds for directions of the force feedback and the perceived amount of directional force as well.

Figure 1. The TouchBall interface (actual implementation).

DEVICE DESIGN

TouchBall mostly resembles a conventional trackball except that it houses a set of motors in two orthogonal directions in order to provide active motion. Figure 2 shows the schematic. The controller is designed such that the thumb is to be placed on the top of the ball in a comfortable manner. The motors are controlled by an MCU, namely 20MHz 20MIPS ATmega48, which generates a PWM signal and communicates with a host computer through a Bluetooth module. The entire design is relatively light (200g) and compact with small sized motors, a solid trackball (100g) and associated control electronics (although our current design detaches the electronics). The device generates a low but audible humming noise (comparable to a low cell phone vibration noise). One of our assumptions in the normal use of this device is that user's gripping force, including the force applied to the trackball through the thumb, will not vary too much among different users [6]. While the device was capable of generating torque of up to ~325 mN.m (motor itself could generate max. 65 mN.m, gear ratio 1:5), in the following experiment, we consider the "perceived" directionality and force generated by the device.

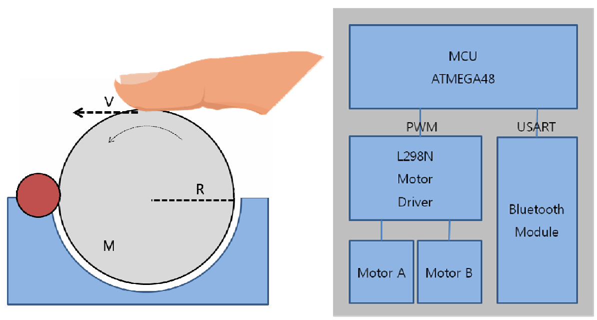


Figure 2. The schematic of the TouchBall (left). The user is to feel direction and a small amount of frictional force acting in the direction tangent to the rotating direction. The right figure shows the hardware control architecture.

EXPERIMENT 1

The goal of the first experiment is to derive the smallest detection threshold for directional feedback for this device. Detection threshold is one of the most basic criteria in measuring human perception [5, 7] and will also provide a yardstick for implementation feasibility as a compact hand-held mobile device. We have designated eight ego-centric directions for which the detection thresholds were investigated, North (N), South (S), East (E), West (W), North East (NE), South East (SE), South West (SW) and North West (NW).

Procedure

Ten paid subjects (8 men and 2 women) participated in the first experiment with the mean age of 25.5. We had the subjects (all right-handed) only use their left hands (or thumbs). Our basis was the work of Tanaka et al. [2] who reported no statistically significant differences in task performance between the right and left hands. While our device is different and skin based (Tanaka's device was kinesthetic or inertial), our main experimental purpose was not in investigating differences from handedness. The reason for choosing the "left" hand was based on our prospect that the device would be "used" by the left hand, while the right (dominant) carrying out other tasks (e.g. mouse cursor control).

The subject was seated before the computer monitor and was asked to hold the device and place one's thumb over the TouchBall comfortable, and apply a "just enough" stopping force (and feel the stimulation) as the track ball started to turn throughout the experiment. Although no fixture or explicit measurement was used, no particular shifts in the subjects' light grips were observed nor reported. The presentations of the directions were randomized.

In order to measure the detection threshold, we applied the 3 Interval, Forced Choice, One-up, Three-down Adaptive method [8]. In this method, three consecutive correct answers (e.g. subject correctly stating the actual direction of the ball among the eight possible) resulted in lowering the amount of stimulation. One incorrect answer would increase the stimulation likewise. The amount of increase or decrease in the stimulation was fixed (0.2V or equiv. torque). In each trial for a particular directional feedback, a subject was given three stimulation intervals separated by 250 ms, during which only one of them would carry an actual stimulation lasting 1000 ms. This assignment was random as well. To avoid confusion on the part of the subject, the current interval (i.e. which of the three) was displayed on the monitor. The initial stimulation was made sufficiently large and the detection threshold (measured in torques applied) was set, at a level where the subject made the second wrong answer during the trial. The latency or exact response characteristic of the device was not measured, but did not present any problems in the experiment. A trial for each direction lasted about 5 to 7 minutes and the whole experiment took about 2 hours.

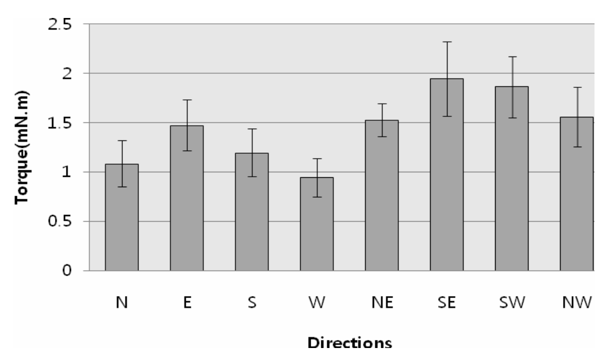


Figure 3. Detection thresholds (in torques applied) for different stimulation directions. Statistically significant difference existed between the upright and diagonal directions.

Results

Figure 3 shows the detection thresholds for the 8 different stimulation directions. ANOVA has revealed that a statistically significant difference existed between the group of upright directions (i.e. N, E, S, W) and the diagonal (i.e. NE, SE, SW, NW) with $p = 0.008$ ($F = 7.58$). Thus, more force feedback was needed in general for the diagonal directions. In particular, the W showed a significantly lower detection threshold compared to other directions (no other directions were statistically distinguishable by itself) with p = 0.039 (F = 4.44). It is consistent with findings from another work with a mobile torque display [2] who found that human hand's sensitivity was relatively lower in the diagonal direction, high in the west (left), and low in the east (right). All the detection thresholds were below 2.5mN.m, way below the maximum capacity (~65mN.m) of the small motor used in our device, which hints for a possibility of even further miniaturization.

EXPERIMENT 2

The second experiment was conducted in order to estimate the perceived intensity of the inertial stimulation, and any qualitative differences for different stimulation patterns. Since the direct and accurate measurement of the perceived intensity is practically infeasible, our measurement was subjective and indirect, relying on the Absolute Magnitude Estimation methodology by [10]. Three independent variables, namely the stimulation wave pattern (3 types), maximum velocity of the trackball (2 types, which amounts roughly to the magnitude of the force feedback) and directions (8 types) (also see Table 1).

Procedure

Twelve paid subjects with the mean age of 26 (9 men and 3 women, different from the first experiment) participated in this experiment. The subjects were given 48 different types, representing 3 factors, of stimulations (see Table 1) in a random order, each lasting 1000 ms. Subjects were asked to name the direction of the stimulation, among the eight possible, and rate the intensity by a numbered score in one's own scale. Thus, no reference nor guideline was given for the intensity rating. Three sessions (each consisting of the 48 randomly ordered stimulations) were carried out for each subject.

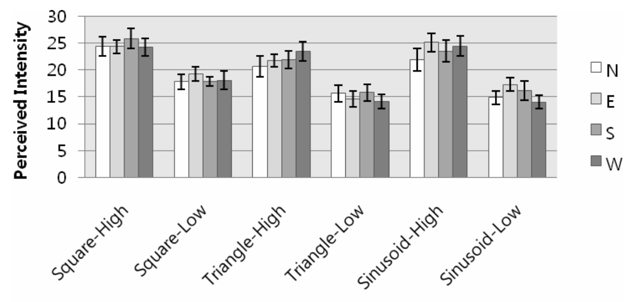
Factor	Types / Levels
Stimulation wave pattern	Square, Triangle, Sinusoid (1Hz)
Max. motor velocity reached	High (14.2 cm/s) and Low (7.1 cm/s)
Directions	N, E, S, W, NE, SE, SW, NW

Table 1. Independent variables and their levels for the second experiment.

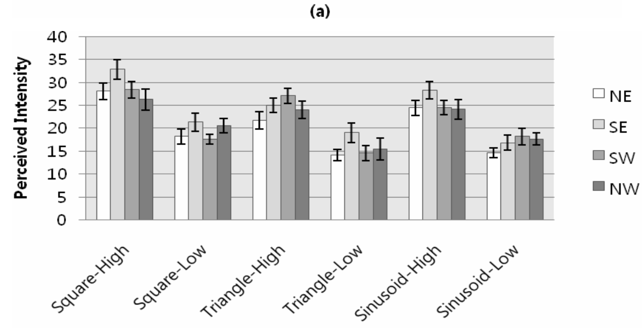
Since there was no trial session for this experiment, the data from the first session was purposely discarded, and the responses from the second and third were merged using a geometric mean. The geometric mean for the whole subjects (Mg) were divided for that of each subject i (Ms_i) to yield $Mg/Ms_i = Mn_i$. This value was multiplied to the data for the corresponding subject for normalization [11]. Likewise to the first experiment, subjects wore headphones to block any ensuing sound from the device.

Results

Perceived intensity: Figure 4 shows the perceived force feedback intensities across different independent variables. ANOVA revealed that there existed statistically significant ($p < 0.001$, $F = 14$) difference according to the type of the wave pattern. The square wave produced the highest perceived intensity, and this was attributed to the fact that square wave exhibits the most differential acceleration translating to a higher resulting force. In a similar vein, the level of the maximum motor velocity also showed statistical difference ($p < 0.001$, $F = 260$), namely the high level producing higher perceived intensity and vice versa. On the other hand, statistical differences among the directions with regards to the perceived intensity were observed.



(a)



(b)

Figure 4. Perceived intensities different independent variables (stimulation wave form, maximum motor velocity used, and directions).

Perceived accuracy for directions: Figure 5 shows the percentages of the correct answers for identifying the direction of the stimulation. The second factor (the maximum motor velocity used) naturally was important for better perception of directions ($p < 0.002$, $F = 14.32$), while, similarly to the first experiment, the overall performance was better for the upright directions in comparison to the diagonal. This suggests the need for different rendering methods in different stimulation directions.

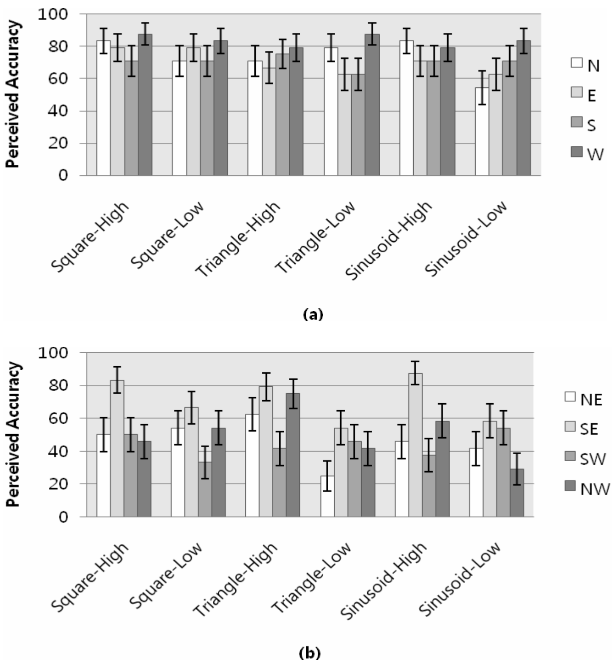


Figure 5. Perceived accuracy for the stimulation direction across different independent variables.

CONCLUSION

In this paper, we presented a trackball based touch-haptic interface which leveraged upon the sensitivity of the human tactile sensation, which lead to a compact and hand-held implementation. We empirically demonstrated that it would be possible to convey 8 directionality information, using the proposed device (at least using the left hand). This bears significance because this was despite the hand-held device being simple and capable of only relatively low amount of stimulation, by relying on the frictional force through our sensitive skin. The provision of 8 directions suggests that it can be applied to induce richer interactive experiences in various applications, but also will require differentiated control. As for future work, we plan to investigate how the device can effectively be combined with other modalities, develop rendering algorithms for simulating sustained forces and deploy it for an actual application (e.g. sports games).

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